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Recent Developments of Emission Control Technology in the United States for Fossil Fuel Combustion Sources

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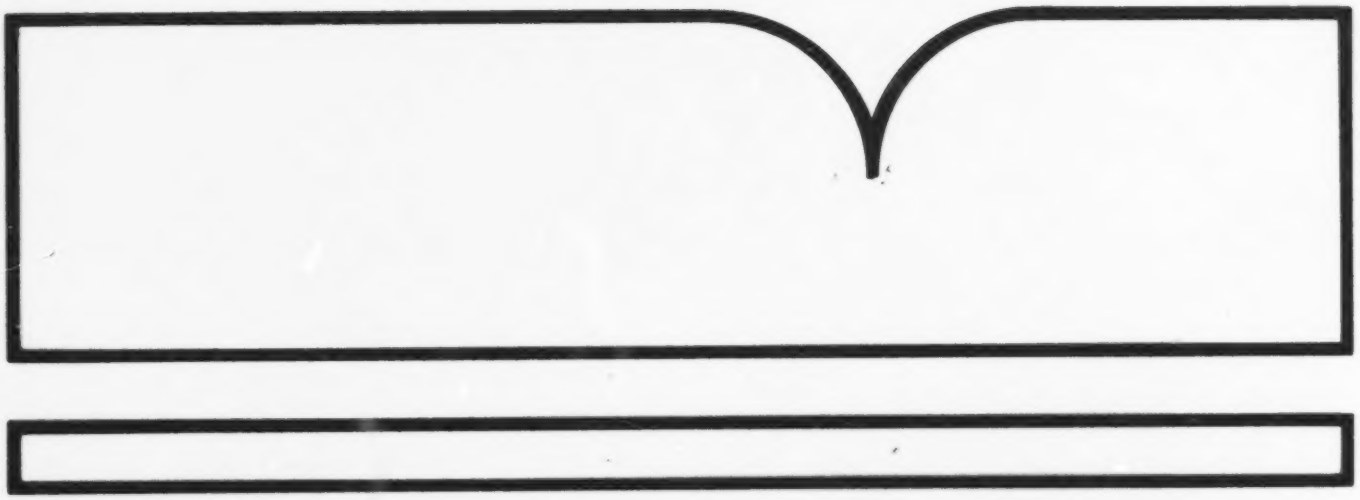

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16. ABSTRACT The paper discusses control of air pollution from fossil fuel combustion. Until recently, this meant abatement of smoke (particulate), sulfur dioxide, and oxides of nitrogen. With growing concern about global climate change, carbon dioxide has been added to the list. The paper includes Discussions of such controls and control systems as wet and dry scrubbers, fabric filters, electrostatic precipitators, physical coal cleaning, flue gas desulfurization, selective catalytic reduction, limestone injection multistage burners (LIMB), reburning, E-SOx and ADVACATE.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Emission	Carbon Dioxide	Stationary Sources	14G
Fossil Fuels		Particulate	21D
Combustion			21B
Particles			
Sulfur Dioxide			07B

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RECENT DEVELOPMENTS OF EMISSION CONTROL TECHNOLOGY IN THE UNITED STATES FOR FOSSIL FUEL COMBUSTION SOURCES

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INTRODUCTION

This paper will discuss control of air pollution from fossil fuel combustion. Until recently this meant abatement of smoke (particulate), sulfur dioxide (SO_2), and oxides of nitrogen (NO_x). With the growing concern about global climate change, carbon dioxide has been added to the list. This section, the introduction, will review the state of the art for control of each air pollutant and the following sections, covering the EPA and other technology under development, will review primarily near-term technology.

Particulate Control

Three types of devices--scrubbers, fabric filters, and electrostatic precipitators--constitute conventional particulate control. For large power plants, most boilers use electrostatic precipitators (ESP's) but fabric filters have gained acceptance especially for control of high resistivity fly ash. Older ESP's were designed to collect 98 to 99% of fly ash and used three or four electrical sections in the direction of gas flow to accomplish it. Newer ESP's are being built with up to six sections and can achieve 99.5 to 99.9% collection of fly ash. Larger ESP's are also built to collect problem fly ashes such as those from coals low in sulfur and/or low in sodium. Not troubled by ESP-problem fly ashes, fabric filters always achieve

high collection efficiencies (>99.5%) but have a much lower space velocity leading to sizes and costs larger than those for ESP's in many applications. Scrubbers require high pressure drops (>10 in. H_2O or 2.49 kPa) to achieve high collection efficiencies and are generally more expensive than either ESP's or fabric filters. However, in many industrial combustion applications, scrubbers are favored because the particulate is flammable (e.g., high in carbon) or is sticky (e.g., contains unburned oil) or because they can provide concurrent control of gaseous pollutants.

Sulfur Dioxide Control

Of the three types of SO_2 control technologies--precombustion, combustion, and post-combustion--precombustion physical coal cleaning is the most extensively used in the United States. The current coal-fired generating capacity in the U.S. is approximately 308 GW produced by nearly 10,500 units. Physical coal cleaning is used to remove from 10 to 30% of the sulfur content of coal prior to combustion for roughly 30% (210 million tons) of the 700 million tons of coal consumed annually.

In-combustion SO_2 control is one of the recent developments and will be discussed below.

The most significant post-combustion technology in terms of SO_2 emission reduction for utility boilers is flue gas desulfurization (FGD). Table 1 summarizes the number and installed capacity of FGD-equipped units that are installed or planned by the end of 1988. The 66,000 MWe of FGD in operation represents slightly over 20% of the coal-fired generating capacity.

Table 2 shows FGD systems in the U.S. as a function of throwaway product versus saleable product, regenerable versus nonregenerable, wet versus dry, and the chemical regent used. The U.S. utility preference is for nonregenerable, calcium-based, wet slurry processes that produce a waste product for disposal. Within the sorbent category, limestone is preferred. Dry scrubbing has recently evolved from an emerging technology to more than 7% of the total FGD capacity.

The application of FGD systems with respect to coal sulfur content can be characterized by three sulfur ranges:

- low-sulfur coal (<1%)
- medium-sulfur coal (1-3%)
- high sulfur coal (>3%)

Table 3 provides a breakdown on this basis. It is evident that about 50% of FGD systems are low-sulfur coal applications.

As a final look at U.S. utility FGD, Table 4 compares selected data of present (1985) and future (1990) installations. The only observable trends are a slight decrease in coal sulfur content (owing to increased use of low-sulfur Western U.S. coals) and an increase in SO_2 removal efficiency, reflecting more stringent SO_2 regulations for new facilities.

Nitrogen Oxides Control

Unfortunately, the application of NO_x controls in the United States is not as successful as for SO_2 controls. When the first New Source Performance Standards (NSPS) were as established in 1971 for utility boilers, the impact on industry was simply to enlarge the fireboxes for less intense combustion. By 1979, the NSPS were revised by lowering allowable NO_x emissions by 14% for Eastern coal and 28% for Western coals, and were based on combustion air staging and first generation low-NO_x burners.

Noticeably absent is the application of in-furnace technologies used in Japan and post-combustion selective catalytic reduction technology now becoming widespread in West Germany and used extensively in Japan. As a result, the NO_x control technologies emerging in Europe are for us a recent development. Table 5 illustrates the lack of application of high NO_x removal technology in the U.S.

Inasmuch as the installed NO_x technologies are all in-combustion, the U.S. suppliers of NO_x control technologies are exclusively boiler and burner manufacturers. Low-excess air firing is likely used for fuel efficiency and economy more than NO_x control. Reductions of up to 10% are reported. Staging the combustion air at a cost of only $2-5 per kW also reduces NO_x emissions. In conjunction with low excess air, an EPA study[1] of 22 units showed an average of 37% NO_x reduction. Low NO_x burners, which delay the fuel/air mixing, have been used in the U.S. since the late 1970's and have shown up to 50% reduction in NO_x at a cost of $5/kW.

EPA SO_x/NO_x TECHNOLOGIES UNDER DEVELOPMENT

Since there are numerous SO_x/NO_x technologies under various stages of development in the United States, it is the intent here to survey those being funded by major research programs, since they are more likely to become commercial within the next 5-10 years. Major research programs other than that of EPA are covered in the next section. This section covers EPA activity and especially the technology "limestone injection--multistage burners" (LIMB) which will be available in less than 5 years.

EPA is currently operating two concepts on a pilot basis: the E-

SO_x and ADVACATE processes. The E-SO_x process involves upgrade of an electrostatic precipitator (ESP) and insertion of a lime slurry spray nozzle in the eliminated first stage. A slipstream demonstration is scheduled for late 1988 through 1989. The ADVACATE process avoids injection of slurries by first converting lime and fly ash into a calcium silicate solids mixture with 20-30% moisture. Pilot evaluations have shown 50% utilization of sorbent in-duct and 80-90% utilization with a fabric filter. The process is currently in negotiation for a license with one vendor.

EPA has two processes at the demonstration scale: LIMB (which is discussed in detail below) and reburning. Reburning is a NO_x control process which introduces a small part (up to 20%) of the fuel after the main combustion area. The reducing zone produced by this second fuel addition changes approximately 50% of the NO_x from the main combustion area to nitrogen. EPA is planning one reburning demonstration in the U.S. and has recently concluded negotiations to partially support a reburning demonstration in Russia.

LIMB Introduction

The objective of these processes is to capture at least 50% of the SO_2 in a flue gas stream at a cost which is competitive with wet or dry FGD. In addition, LIMB is targeted to lower emissions of NO_x by 50% with low NO_x technology. While ADVACATE and E-SOX are still being studied at the pilot scale, LIMB has progressed to full scale demonstration. Advancement to demonstration scale has come as the result of many years of EPA sponsored R&D including tests at large pilot and prototype facilities. The LIMB program has consisted of five activity areas; namely, fundamentals, pilot and prototype scale tests, modelling, cost analysis, and demonstration.

Fundamentals have focused on the kinetics of potential LIMB reactions (e.g., calcination and sulfation) and on properties of limestone and limestone products to identify and optimize properties providing high reactivity for SO_x capture. Pilot and prototype scale tests have provided information on the effect of the furnace conditions on LIMB and on the effect of LIMB on furnace operations and on the operation of the extant particulate collection device which is almost always an ESP. Modelling is obviously used to analyze and extrapolate test data and to provide input to the fourth area of cost analysis which compares LIMB to alternatives. Finally, demonstration provides the data necessary for generalization of the technology to the private sector.

The LIMB program calls for demonstration at two sites: a wall-fired power plant, and a tangentially fired (T-fired) power

plant. The wall-fired plant is described below. The T-fired plant is a nominal 140 MWe unit constructed by Combustion Engineering and located in Yorktown, Virginia. Because of the difference in firing systems, the flow patterns in wall- and T-fired boilers are significantly different. The flow pattern affects the mixing and the temperature history of injected sorbent particles. Thus, it is essential to test LIMB with these two types of firing systems which are the only two major types of firing systems for large scale utility boilers.

Conclusions from pilot and prototype testing which preceded the demonstration projects are:

1) Calcium hydroxide is a superior SO_2 sorbent to either calcium carbonate (limestone) or calcium oxide; the performance of calcium hydroxide can be enhanced by the addition of calcium lignosulfonate (a surfactant).

2) The optimum injection temperature into a typical boiler furnace for calcium hydroxide is 2300°F (1260°C); incorporation of calcium lignosulfonate allows injection at slightly higher temperatures without adverse effects.

3) Deposits formed in the furnace in high temperature zones as a result of sorbent injection are soft and are usually removable with normal or increased sootblowing operation typical of a power boiler furnace.

4) Injection of calcium hydroxide increases the resistivity of the fly ash and thus decreases the efficiency of an ESP; the resistivity and efficiency can be restored by humidification which will also reactivate unused calcium oxide for further SO_2 capture at low temperatures.

5) The reactivity of commercial calcium hydroxide varies enough to affect attainment of SO_2 capture objectives; the most reactive calcium hydroxide in the area of the LIMB demonstration was found to be that supplied by Marblehead Lime Co.

LIMB Demonstration

The site for the LIMB demonstration is the Edgewater Unit 4 of Ohio Edison Company located in Lorain, Ohio. The boiler is a nominal 105 MWe unit made by Babcock & Wilcox. It is a radiant, wall-fired, Carolina furnace burning eastern bituminous coal. It has been in operation since June 1, 1957. The boiler has 12 burners fired from a single wall in a three column by four row array. The burners were B&W circular burners until recently changed to B&W XCL low NO_x burners for the "MB" (multistage burner) part of the LIMB program. Particulate is collected by a six field Lodge Cottrell ESP which is only 4 years old.

With respect to the "LI" (limestone injection) part of LIMB, the system for injection delivers sorbent to three levels in the boiler. These levels are elevations 181, 187, and 191 which have eight nozzles each in the front wall. In addition, there are two

nozzles on each side wall at elevation 187 and 3 ft (91 cm) from the front wall. Elevation 181 is slightly below and elevation 187 is slightly above the "nose" of the boiler. It is in this regime that the injection temperature of 2300°F (1260°C) is available on average. Obviously, the temperature varies across a horizontal cross-section of the boiler because of heat transfer to the wall-cooled walls.

Accurate determination of LIMB effectiveness is dependent on measurements of sorbent feed rate, outlet SO_2 concentration, and inlet sulfur concentration as determined by coal feed rate and coal sulfur concentration. Sorbent feed rate was measured by differential weight loss feeders. For the outlet sulfur concentration, a continuous emission monitor analyzes the flue gas between the stack and the induced draft fan after the ESP. In this monitor, gas is extracted through a filter in the stack and another filter in a heated box before being drawn to a UV analyzer. Both filters are hot (approximately 300°F or 150°C) to avoid reactions of unused sorbent on the filter, and contamination is slight because the boiler's ESP located upstream is highly efficient. The coal feed rate is determined by computation from the boiler heat rate using equations for the design of the Edgewater boiler which B&W considers proprietary. The coal sulfur content is determined by sampling of the coal just before injection into the furnace. As noted above, coal feed rate and coal sulfur concentration are used to compute the inlet SO_2 concentration which is verified by the outlet monitor during periods without sorbent injection and well after any periods of sorbent injection.

All the elevation 181 capture data taken are shown in Figure 1 versus the calcium to sulfur molar ratio. By dividing the SO_2 capture by the calcium to sulfur ratio, the utilization of calcium oxide is obtained and is plotted in Figure 2. Note that utilization decreases slightly with calcium to sulfur ratio in an approximately linear fashion. Figure 3 shows the data for the Marblehead commercial sorbent only and Figure 4 the data for sorbent modified with calcium lignosulfonate. These two figures present both the SO_2 capture and the calcium oxide utilization as a function of the calcium to sulfur ratio.

Statistical analysis of the data provides a useful interpretation of the results of the Edgewater demonstration to date. Figures 5 and 6 show the predicted SO_2 captures for untreated and treated sorbents, respectively. The middle line is the average prediction and the outside lines show the prediction for upper and lower bounds as defined by two standard deviations from the average. These figures show that LIMB easily meets its objective of 50% sulfur capture at a calcium to sulfur ratio of less than 2.0. The average lines for both untreated and treated sorbents are shown together in Figure 7. The sorbent treated with calcium lignosulfonate is more effective than the untreated sorbent

although the difference is small. Comparison of the upper bound of the untreated sorbent with the lower bound of the treated sorbent shows that there is a positive difference at calcium to sulfur ratios above 1.5.

OTHER TECHNOLOGY UNDER DEVELOPMENT

Particulate Control

Considerable effort has been directed toward improvement of ESP technology. The primary reason was the application of ESP's to fly ashes from low sulfur coals which had become more popular to lower SO_x emissions. At first the development of the hot-side ESP (on the hot side of the air preheater) was successful. However, performance degraded with time because of depletion of charge carriers (mostly sodium) in the residual fly ash layer on the collection plate. The depletion problem, combined with mechanical problems, has eliminated most interest in this approach.

Another approach is the two stage precipitator. The concept is to separate the charging and collecting functions of the ESP in order to optimize both. The problem is that the precharger can suffer from the same electrical condition--back corona--that can limit a normal ESP. A number of solutions have been proposed and tested but the most successful has been the cold pipe precharger. By cooling the electrodes which ordinarily have back corona, the electrical conditions are improved and back corona is avoided. This concept has been successfully tested at the large pilot scale but to date no large scale demonstrations are planned.

Progress has also been made in improving fabric filter technology. The key to improvement has been new fabrics which allow the use of pulse-jet baghouses having higher space velocities (air-to-cloth ratios) leading to smaller size and lower cost. Conventional technology for power plants uses cleaning methods such as reverse air or reverse air/shake which lead to low air-to-cloth ratios. Pulse-jet cleaning would lead to higher air-to-cloth ratios but generally require felt fabric filters. Until recently only fibrous glass, Nomex, and Teflon felt were available. However, fibrous glass bags often yield poor bag life, Nomex is susceptible to hydrolysis in flue gas, and Teflon is expensive. There are now available felts of homopolymer acrylic (Dralon T) and polyphenylene sulfide (Ryton) which have been successfully used in power plant application. While the acrylic appears suitable only for lower temperature

applications, the Ryton performs well in flue gas environments up to 400°F (204°C). The Ryton felt can be on a Ryton scrim or on some other scrim. The former has been successfully developed and tested in Japan and the latter in the U.S.

SO_x Control

America's clean coal commitment is a national effort involving the federal government, state governments, and private sponsors. Between 1986 and 1992, the nation will likely invest more than $6 billion to develop and demonstrate the emerging new generation of clean coal concepts. Slightly more than $2 billion of this funding will be provided by the U.S. Department of Energy in its Clean Coal Program. Nearly double that--$3.86 billion--will be invested by private sources. Two states alone, Illinois and Ohio, are expected to commit more than $800 million.

Approximately 80%, or $4.9 billion of the $6 billion, will be committed to specific field projects that are intended to demonstrate the large-scale viability of these new technologies. The remainder consists of privately and publicly financed research and development programs that are focused specifically on the cleaner use of U.S. coal. The nine projects in Table 6 were a result of the Clean Coal I Program administered by the U.S. Department of Energy (DOE). These projects represent a nearly $1 billion investment and is the first of three planned phases in clean coal demonstration.

For SO_2 control a considerable effort is underway in low capital cost retrofit technologies. The DOE has embraced several alternate in-duct slurry injection concepts including two-nozzle delivered lime slurry systems and a rotary atomizer system. The Confined Zone Dispenser (CZD) by Bechtel, Hydrate Addition at Low Temperature (HALT) by Dravo, and In-Duct Scrubbing (IDS) have all completed pilot slipstream evaluation and await funding for larger scale demonstrations. The Electric Power Research Institute (EPRI) completed evaluation of dry sodium injection at their Arapaho pilot units and have published results[2] with anticipated costs.

Other innovative concepts (e.g., ammonia-enhanced spray drying, circulating limestone bed absorbers, and limestone-injection fabric filters) are under evaluation funded by the Ohio Coal Development Office (OCDO) who is also funding the E-SO_x slipstream evaluation.

NO_x Control

New NO_x technology again lags SO_2 technology. The EPRI is co-funding some evaluations of in-furnace reburning with the Gas

Research Institute (GRI). Reburning consists of combustion of about 80% of fuel in one combustion zone, followed by injection of 20% of the fuel in a fuel rich zone, where the majority of fuel-borne NO_x is reduced to N_2. Burnout in a final combustion zone follows. If the secondary zone fuel is nitrogen-free (e.g., natural gas), the resultant NO_x emissions should be near those for thermal NO_x. In-house evaluation by EPA shows that at least 50% NO_x reduction is possible irrespective of inlet conditions.

EPRI is intending to fund construction and operation of 5 to 10 slipstream (1-5 MWe) units for evaluation of selective catalytic reduction (SCR) on U.S. coals. [EPA previously conducted a 5 MWe pilot evaluation in 1979 and EPRI a 10 MWe evaluation in 1982.] Since two SCR projects were submitted for Clean Coal II, EPRI is awaiting the outcome before formal action will be taken.

Combined SO_x/NO_x technologies (other than LIMB) have not received enthusiastic support due to the perceived complexity of operation and solid waste disposal problems. Wet SO_x/NO_x removal has been studied by Argonne National Laboratories and awaits further interest. Combined SO_x/NO_x control in spray drying is currently being evaluated by Argonne for DOE. NOXSO and Copper Oxide processes, regenerable systems using sorbent/catalyst, have completed pilot evaluation by DOE at the Pittsburgh Energy Research Center and are candidates for future clean coal demonstrations. In like manner, the Electric Beam Irradiation (E-BEAM) process has received considerable attention and is a potential future clean coal demonstration.

Carbon Dioxide Control

Direct control of carbon dioxide from combustion does not appear to be promising. The key to this problem is prevention or removal of carbon dioxide from the atmosphere by techniques such as reforestation. Prevention can take the form of a complete substitution for fossil fuels or the substitution of fossil fuels with a higher ratio of hydrogen to carbon. Thus the combustion of natural gas instead of coal would significantly reduce carbon dioxide emissions.

SUMMARY AND CLOSING REMARKS

Particulate is controlled with scrubbers, electrostatic precipitators, and fabric filters. Two stage precipitators and pulse jet fabric filters with special media are new technologies which will increase cost-effectiveness.

Conventional wet and dry FGD is well established SO_2 control

technology in the U.S., while NO_x technology is confined to combustion modifications. Many SO_2 technologies, a few NO_x technologies, and even fewer combined SO_x/NO_x technologies are under evaluation by EPA, by DOE (especially in its Clean Coal Demonstration Program), or by other leading U.S. research programs (e.g., those of EPRI, GRI, Ohio Coal Development Office (OCDO), and other state agencies). One of the most promising of these is LIMB which is being demonstrated on a wall-fired utility boiler. The advantage of LIMB is its ease of retrofit leading to low capital cost and high effectiveness for the cost.

TABLE 1. NUMBER AND INSTALLED CAPACITY OF UTILITY FGD SYSTEMS

Status	No. of units	Total controlled capacity, MW[a]	Equivalent scrubbed capacity, MW[b]
Operational or under construction	150	66,219	62,283
Planned	56	33,989	33,404
TOTAL	206	100,208	95,687

[a] Summation of the gross unit capacities brought into compliance by the use of FGD systems regardless of the percentage of the flue gas scrubbed by the FGD system(s).

[b] Summation of the effective scrubbed flue gas in equivalent MW, based on the percentage of flue gas scrubbed by the FGD system(s).

TABLE 2. SUMMARY OF FGD PROCESS DESIGN

	Operational		Under construction		Contract awarded		Total	
	No.	MW	No.	MW	No.	MW	No.	MW
Throwaway product								
Wet								
Nonregenerable								
Limestone	60	26,008	9	5,564	8	5,406	77	36,978
Lime	39	17,112	-	-	2	2,036	41	19,148
Sodium carbonate	6	1,505	1	550	2	1,100	9	3,155
Regenerable								
Dual alkali	5	1,963	1	265	-	-	6	2,228
Dry (nonregenerable)								
Lime	12	3,893	3	1,510	1	720	16	6,123
Sodium carbonate	1	440	-	-	-	-	1	440
Saleable product								
Wet								
Nonregenerable								
Limestone	2	624	1	165	-	-	3	789
Regenerable								
Wellman Lord	7	1,959	-	-	-	-	7	1,959
Magnesium oxide	3	724	-	-	-	-	3	724
TOTAL THROWAWAY PRODUCT	123	50,921	14	7,889	13	9,262	150	66,072
TOTAL SALEABLE PRODUCT	12	3,307	1	165	-	-	13	3,472
TOTAL WET	122	49,895	12	6,544	12	8,542	146	64,981
TOTAL DRY	13	4,333	3	1,510	1	720	17	6,563
TOTAL NONREGENERABLE	120	49,582	14	7,789	13	9,262	147	66,633
TOTAL REGENERABLE	15	4,646	1	265	-	-	16	4,911

TABLE 3. FGD SYSTEMS BY COAL SULFUR CONTENT

Coal sulfur content	Operational		Under construction		Contract awarded		Committed projections		Total	
	No.	MW	No.	MW	No.	MW	No.	MW	No.	MW
Low	68	30,420	7	4,470	7	4,820	13	8,125	95	47,835
Medium	29	11,008	5	2,890	4	2,480	9	5,131	47	21,509
High	38	16,471	3	960	2	1,961	6	3,620	49	23,012
Undecided	-	-	-	-	-	-	15	7,852	15	7,852
TOTAL	135	57,899	15	8,320	13	9,261	43	24,728	206	100,208

TABLE 4. SELECTED DATA COMPARISON OF PRESENT AND FUTURE UTILITY FGD INSTALLATIONS IN THE UNITED STATES

	December 1985	December 1990
Number of operational units	135	159
Capacity, MW	57,899	71,782
Avg. coal sulfur content, percent	1.90	1.87
Avg. SO_2 removal efficiency, percent	81.1	82.4
Scrubbing process, percent by capacity		
Wet systems (throwaway product)		
Lime[a]	31	27
Limestone[b]	48	50
Dual alkali	4	4
Sodium carbonate	3	5
Dry systems (throwaway product)[c]	8	9
Wet systems (saleable product)[d]	6	5
TOTAL	100	100
Regulatory classification, percent by capacity		
Regulatory class		
More stringent than 6/79 NSPS	21	24
6/79 NSPS	10	14
More stringent than 12/71 NSPS, but less stringent than 6/79 NSPS	33	30
12/71 NSPS	32	28
Less stringent than 12/71 NSPS	4	4
TOTAL	100	100

[a] Includes lime/alkaline fly ash.
[b] Includes limestone/alkaline fly ash.
[c] Includes lime and sodium carbonate processes.
[d] Includes magnesium oxide and Wellman Lord scrubbing processes and limestone processes where a high-grade gypsum byproduct is sold.

TABLE 5. COAL-FIRED UTILITY SCR APPLICATIONS

	No.	Total MWe
West Germany[a]	57	28,700
Japan[b]	26	6,118
United States	0	0

[a] Operating or under construction.
[b] Operating as of 12/87.

TABLE 6. PROJECTS IN THE CLEAN COAL PROGRAM

Sponsor	Technology	Location
American Electric Power	Pressurized Fluid-Bed Combustion Combined Cycle	Ohio
Babcock & Wilcox	LIMB/Sorbent Injection	Ohio
Coal Tech	Advanced Combustor	Pennsylvania
Energy & Environmental Research	Gas Reburn/Sorbent Injection	Three sites in Illinois
Energy International	In-Situ Gasification	Wyoming
General Electric	Gasification with Power Turbine	Ohio New York
Ohio Ontario	Coal-Oil Coprocessing	Ohio
M.W. Kellogg	Combined Cycle Gasification	Pennsylvania
Weirton Steel	Direct Iron Ore Reduction	West Virginia

REFERENCE

1. Ponder, Wade H., "Technologies for Controlling Pollutants from Coal Combustion," presented at the Clean Coal Technology Conference, Arlington, VA, October 7-8, 1985.

2. Economic Evaluation of Dry-Injection Flue Gas Desulfurization Technology EPRI CS-4373, Electric Power Research Institute, Palo Alto, CA, January 1986.

FIGURE 1

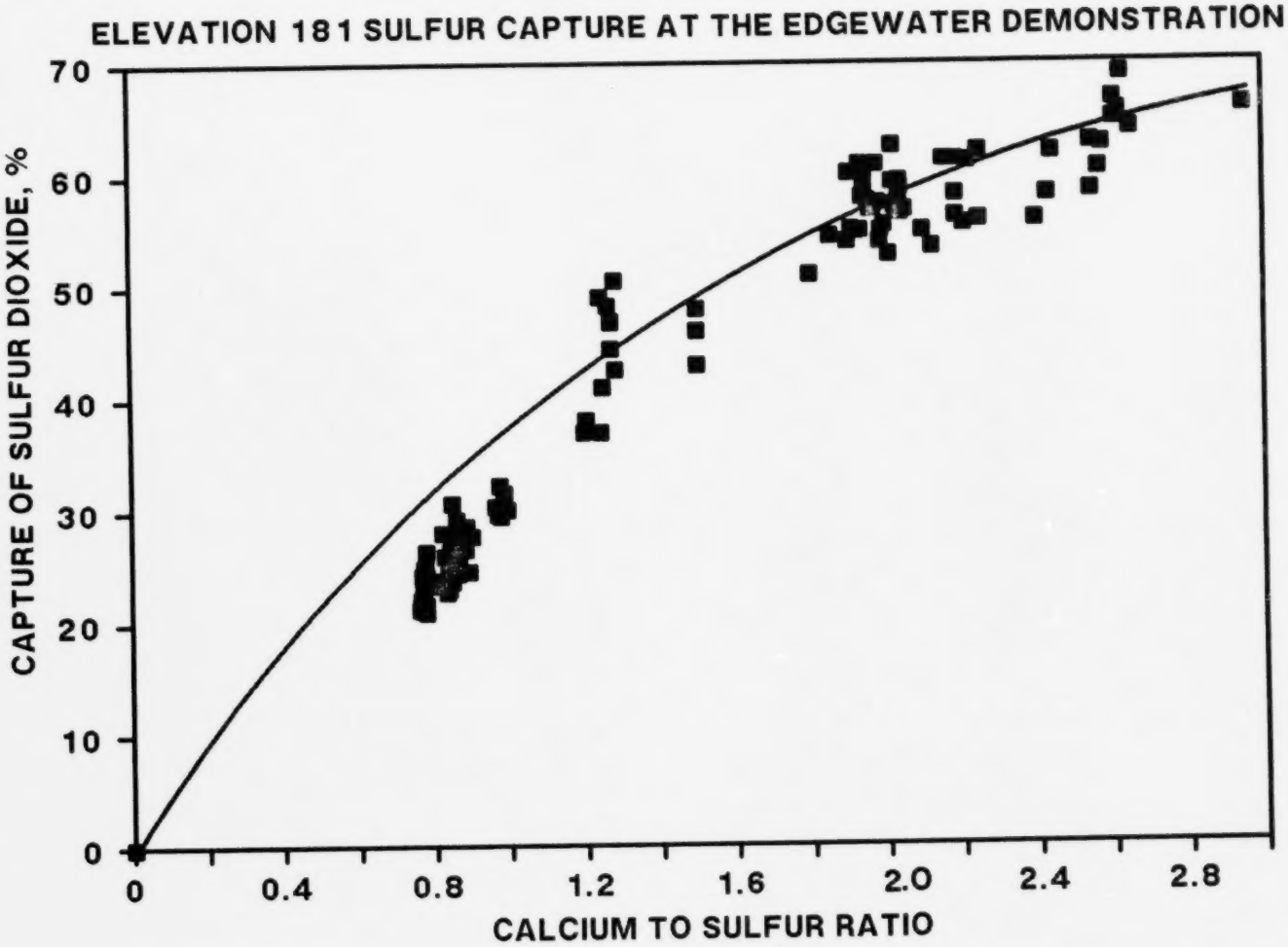
ELEVATION 181 SULFUR CAPTURE AT THE EDGEWATER DEMONSTRATION
CAPTURE OF SULFUR DIOXIDE, %
70
60
50
40
30
20
10
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALCIUM TO SULFUR RATIO

FIGURE 2

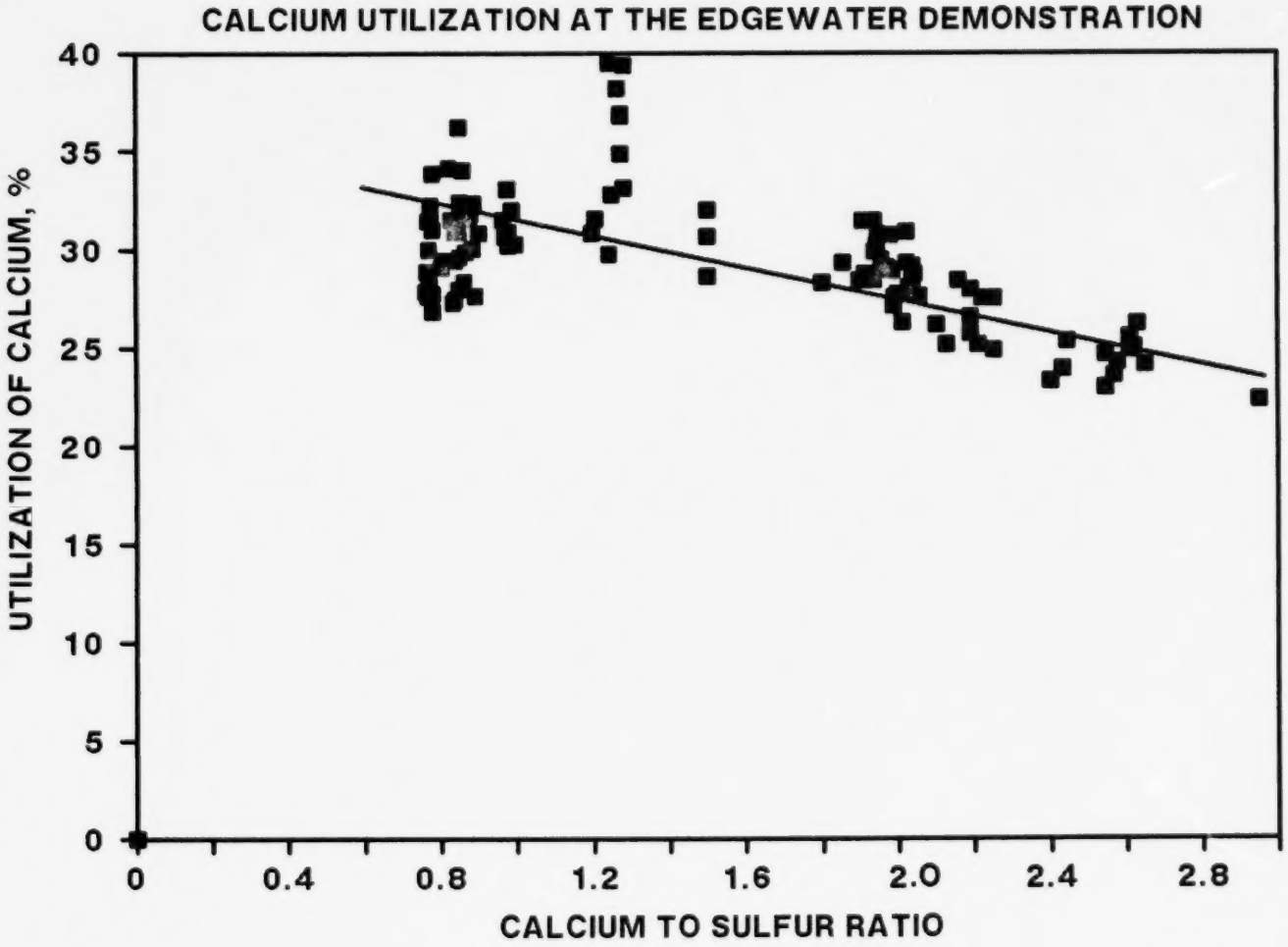
CALCIUM UTILIZATION AT THE EDGEWATER DEMONSTRATION
UTILIZATION OF CALCIUM, %
40
35
30
25
20
15
10
5
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALCIUM TO SULFUR RATIO

FIGURE 3

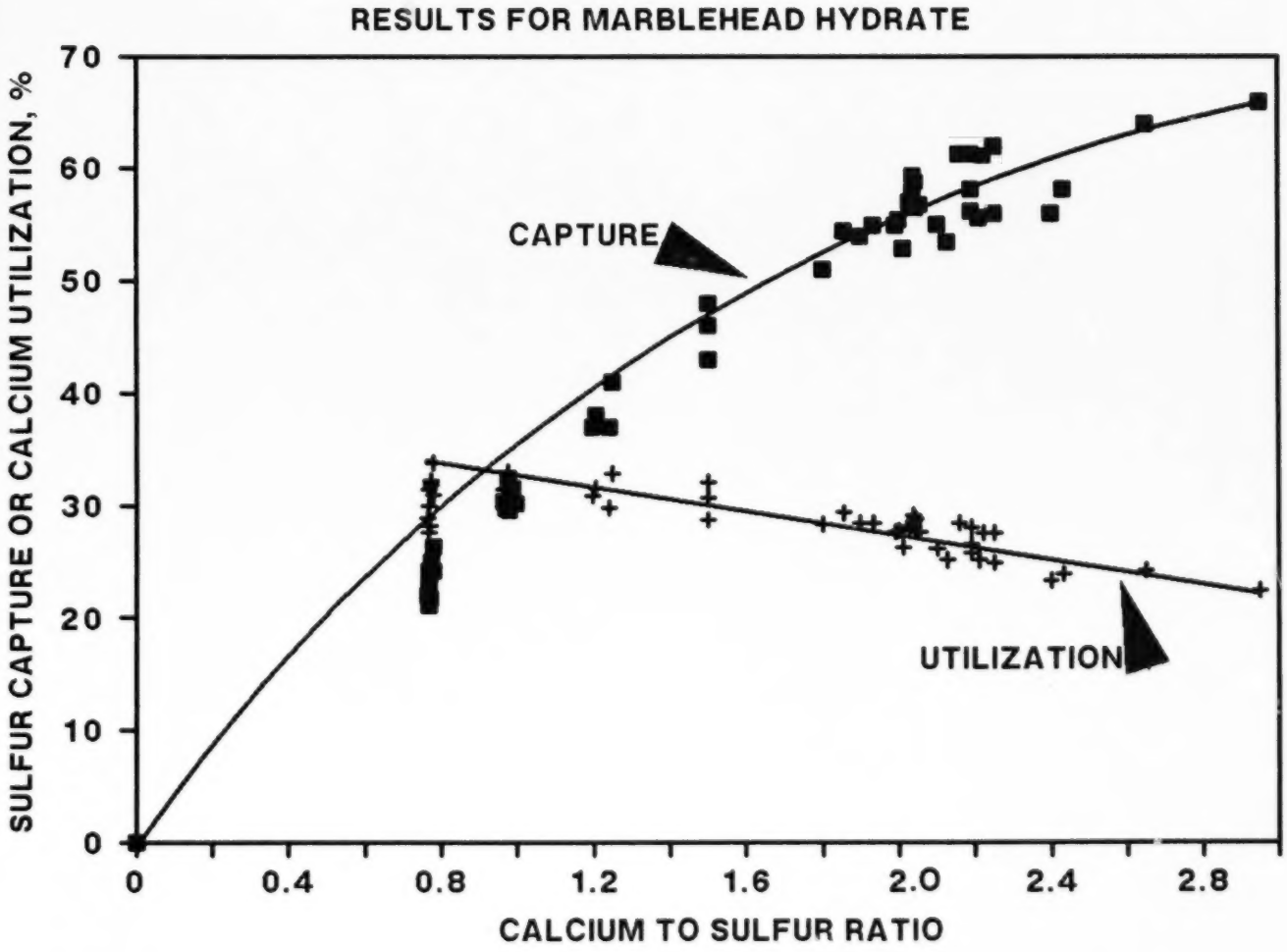
RESULTS FOR MARBLEHEAD HYDRATE
SULFUR CAPTURE OR CALCIUM UTILIZATION, %
70
60
50
40
30
20
10
0
CAPTURE
UTILIZATION
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALCIUM TO SULFUR RATIO

FIGURE 4

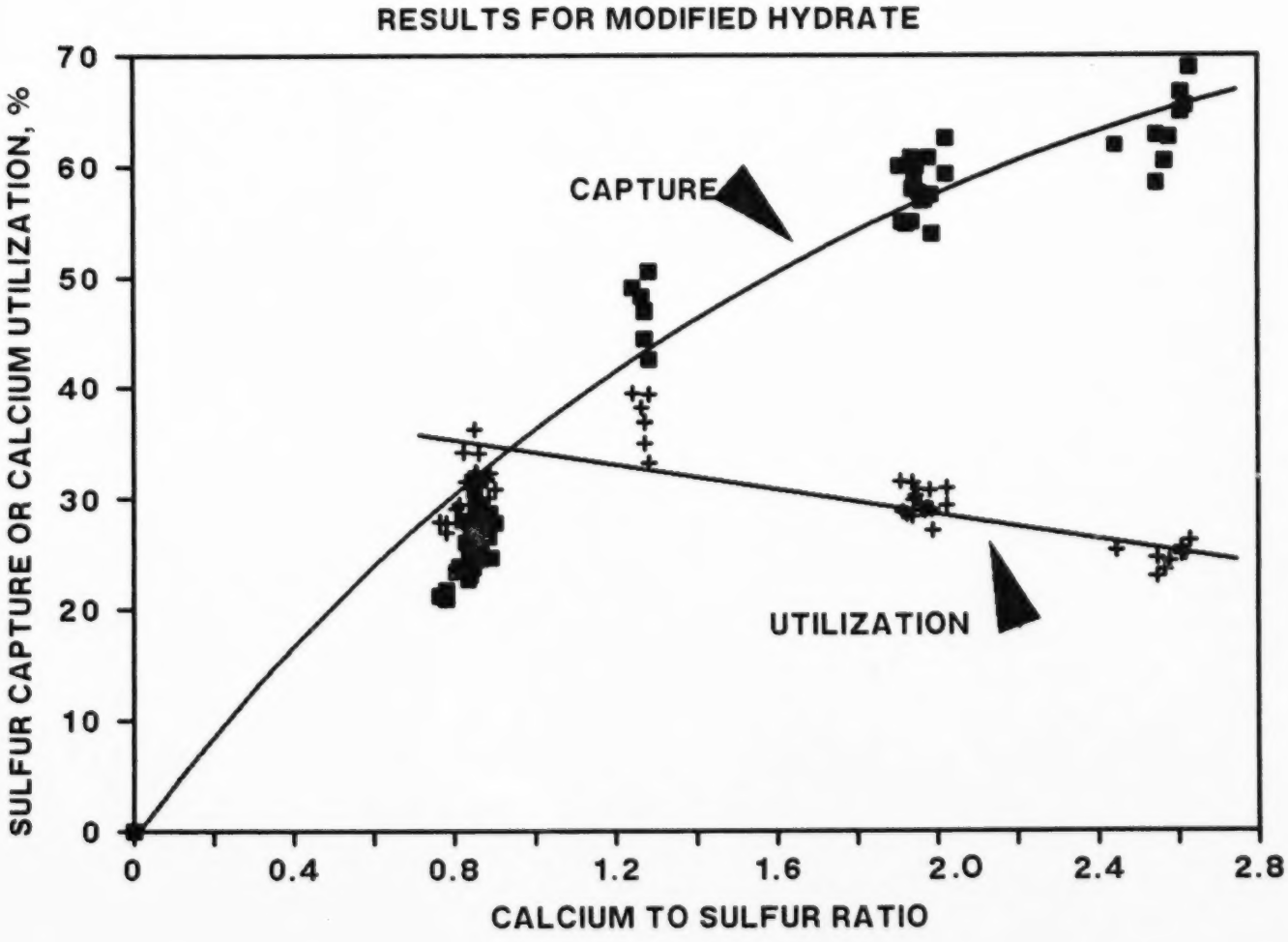
RESULTS FOR MODIFIED HYDRATE
SULFUR CAPTURE OR CALCIUM UTILIZATION, %
70
60
50
40
30
20
10
0
CAPTURE
UTILIZATION
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALCIUM TO SULFUR RATIO

FIGURE 5

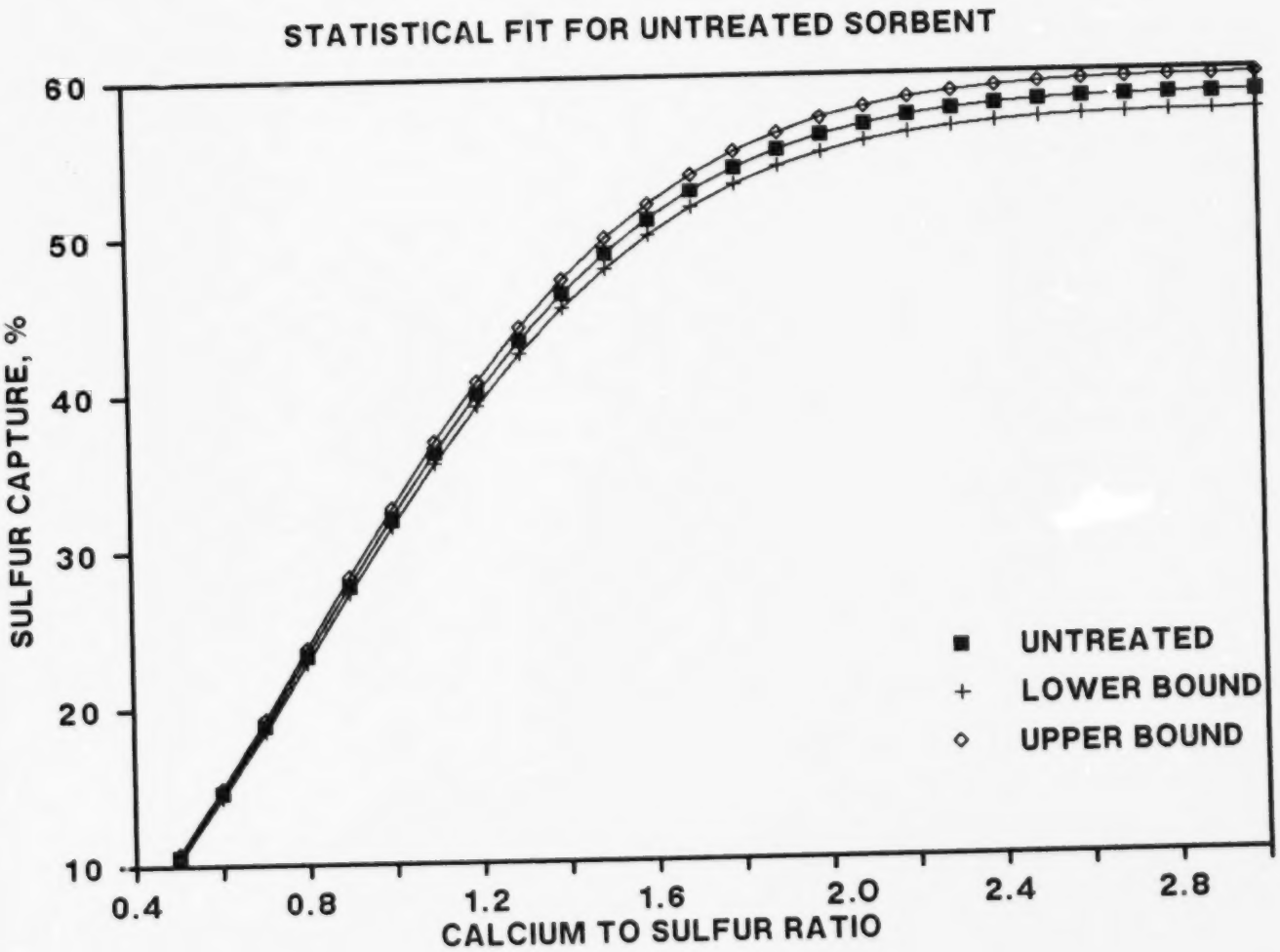
STATISTICAL FIT FOR UNTREATED SORBENT
SULFUR CAPTURE, %
60
50
40
30
20
10
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALCIUM TO SULFUR RATIO
UNTREATED
LOWER BOUND
UPPER BOUND

FIGURE 6

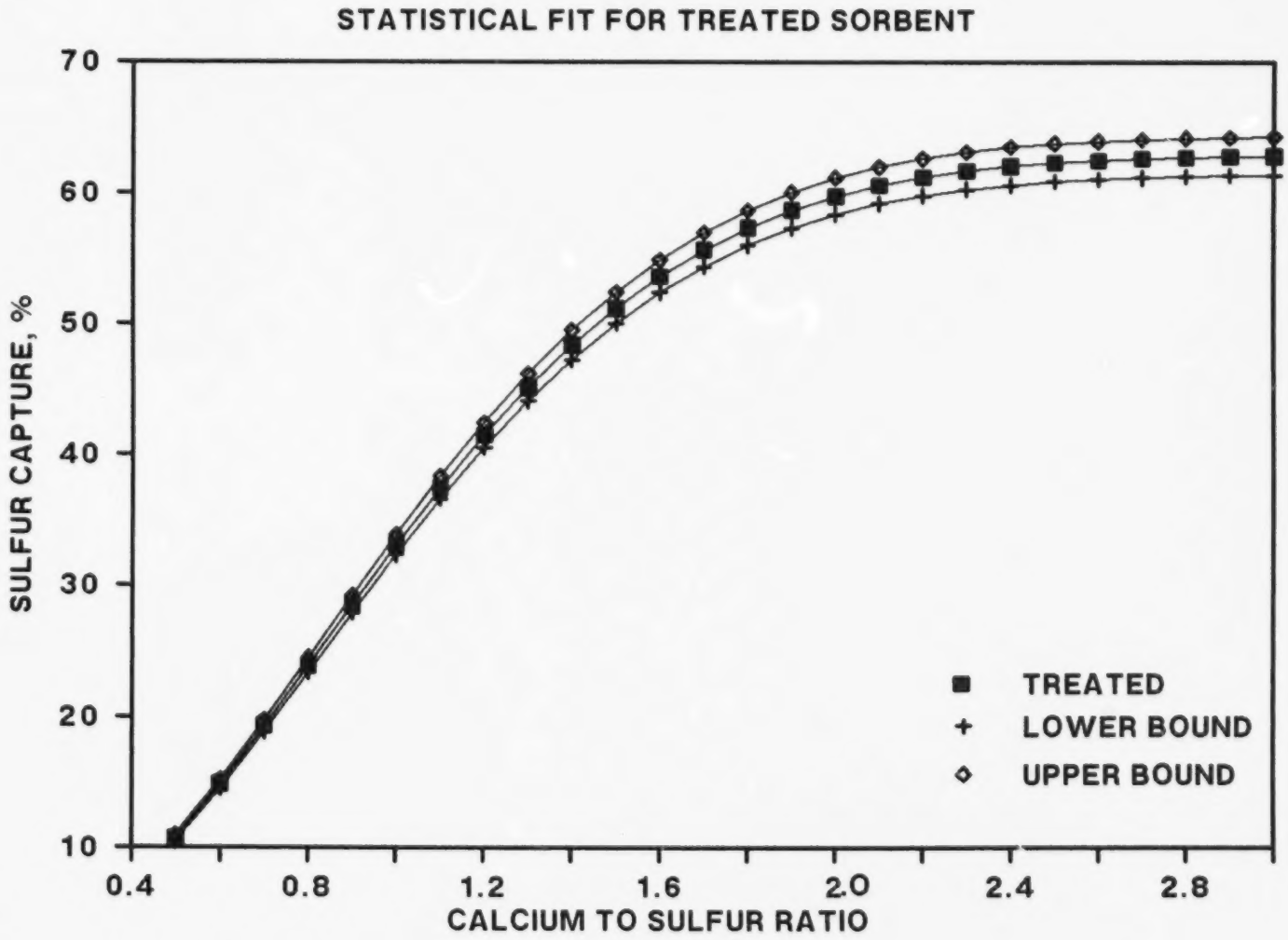
STATISTICAL FIT FOR TREATED SORBENT
SULFUR CAPTURE, %
70
60
50
40
30
20
10
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALCIUM TO SULFUR RATIO
TREATED
LOWER BOUND
UPPER BOUND

FIGURE 7

STATISTICAL FIT COMPARING THE TWO SORBENTS